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Analysis of Current Assessments and Perspectives of ESR Tooth Dosimetry for Radiation Dose Reconstruction of the Population Residing Near the Semipalatinsk Nuclear Test Site

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Semipalatinsk/ESR dosimetry/Low dose exposure/Biological dosimetry/Nuclear explosion test.

Between 1949 and 1989 the Semipalatinsk nuclear test site (SNTS), an area of 19,000 square km in northeastern Kazakhstan, was the location of over 400 nuclear test explosions with a total explosive energy of 6.6 Mt TNT (trinitrotoluene or trotyl) equivalent. It is estimated that the bulk of the radiation exposure to the population resulted from three tests, conducted in 1949, 1951, and 1953 although estimations of radiation doses received by the local population have varied significantly. Analysis of the published ESR dose reconstruction results for residents of the villages near the SNTS show that they do not correlate well with other methods of dose assessment (*e.g.* model dose calculation and thermo luminescence dosimetry (TLD) in bricks). The most significant difference in dose estimations was found for the population of Dolon, which was exposed as result of the first Soviet nuclear test in 1949. Published results of ESR measurements in tooth enamel are considerably lower than other dose estimations. Detailed analysis of these results is provided and a possible explanation for this discrepancy and ways to eliminate it are suggested.

INTRODUCTION

The Semipalatinsk nuclear test site (SNTS) is located in the northeast of Kazakhstan. It covers an area of approximately 19,000 square km. The name of the site originates from the main local city Semipalatinsk (present name is Semey), which is about 150 km east of SNTS. The Soviet Union began atmospheric tests of nuclear devices at SNTS on 29 August 1949. During the whole period of nuclear weapons testing, 456 tests of nuclear devices were conducted at SNTS.[1)] The total energy yield of atmospheric nuclear explosions was about 6.6 Mt TNT equivalent.[2)] Some settlements along the southern and eastern SNTS borders lie within the estimated trajectory of the radioactive releases from the largest above-ground explosions. A population of 30,000–40,000 is estimated to live in this area. The radiation exposure to people who lived close to the SNTS resulted mostly from above-ground explosions. There is a significant number of publications devoted to the radiation dose assessment for the local population residing in the vicinity of SNTS, see, for example.[1–8)] Most publications conclude that the bulk of the radiation exposure to the population resulted from three tests conducted August 29, 1949 (22 kt), September 24, 1951 (38 kt), and August 12, 1953 (400 kt). Tables 1 and 2 give some information on the names of the most exposed villages, the number of residents at the time of nuclear testing and estimations of the current number of exposed individuals in each village. Published model estimations of radiation doses received by the local population demonstrate significant discrepancies (compare, for example.[3, 6,7)] According to most model estimations the population of Dolon received the highest doses (about ≥ 1 Gy) although the estimates vary significantly. One possible way to verify a dosimetric model is by methods of individual radiation dose reconstruction. Currently there are two types of individual dose reconstruction methods in use. One is based on measurements of stable radiation induced radicals in tooth enamel with electron spin resonance (ESR); the other is based on measurements of stable chromosome aberrations in blood. It is also possible to verify dosimetric models by comparing model predictions to doses measured with thermo and optically stimulated luminescence (OSL) in different building materials (mostly in red bricks) or radioactive contamination in soil. Both approaches are not free from disadvantages. Teeth and chromosome analyses assume that the individuals selected for individual dose reconstruction statis-

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tically represent the whole population of the village under study. Analysis of building materials is indirect because it requires additional modeling of human behavior for radiation dose assessment.

The aim of this paper is to analyze published results for individual dose reconstruction for populations living in the most exposed villages and to evaluate the validity of their application to the whole population from the point of view of statistical confidence.

ANALYSIS OF AVAILABLE RESULTS OF INDIVIDUAL RADIATION DOSE RECONSTRUCTION

There are three available publications on ESR dose reconstruction for populations residing in the SNTS vicinity.[8–10] Published results of ESR dose assessment and some information on model estimations of doses for the same villages are presented in Table 2. Comparison of the dose values in Table 2 shows that ESR doses are considerably lower than for model estimations; this is especially true for Dolon, where the ESR dose is about one order of magnitude below the predicted value. There are also four papers in which individual doses were evaluated using biodosimetry methods. In three of them,[11–13] cytogenetic methods based on determination of the number of chromosome aberrations showed that doses in Dolon and other villages were close to background values. There was no significant difference between the frequencies for any aberration type in the controls and the inhabitants of Dolon. In the other paper,[14] dose assessment based on the number of micronuclei in lymphocytes showed some elevation of doses for Dolon but still at a factor of 2 below the predicted values.

Table 1. Number of residents in selected Kazakh villages near SNTS.[4]

Settlement	Population in 1956–58 as for 1958
Znamenka	832
Karaul	2,296
Dolon	1,228
Sarzhal	about 2000
Kaynar	about 3000

Table 2. Comparison of the published results of ESR dose estimates for representative subjects in villages and mean of the calculated external dose to the thyroid.[6, 8, 9 and 10]

Village name	Maximum external dose from[6], mSv	Mean of calculated external dose to the thyroid[6] (mGy)	Mean ESR dose (mGy)/ Background adjusted (mGy)
Dolon	1240	956	192/129[1] 224/176[3]
Sarzhal	1300	544	–
Bolshaya Vladimirovka	–	14.9	285/222[1]
Kanonerka	250	162	247/183[1]
Kaynar	50	28	350/300[2]
Novopokrovka	–	18.9	218/156[1]
Karaul	690	300	256/195[1]
Korostely	28	27	–

In contrast to these methods of individual dose reconstruction, methods based on TLD measurements in building materials[15,16] and radioactive contamination of soil[17] provide considerably higher population dose estimations that are in better agreement with the models.

An important question here is what methods of dose assessment are more reliable for the SNTS population: methods of individual dose reconstruction based on ESR in teeth and cytogenetic changes in the blood, or model dose assessment and some other methods based on environmental measurements.

The following are potential problems with interpreting ESR dose reconstruction based on a sample of selected individuals:

- Individual variation in lifestyle and diet
- Exposure from non-uniformly contaminated soil, causing considerable variation in received doses
- Possible delay in the development of permanent teeth because of malnutrition among local populations during World War 2
- Possible false claims of being at the exposure event to to receive monetary compensation
- Mistakes (random and intentional) in the identification of exposed teeth by individuals paid per collected tooth
- Residents with high doses have died already, so that the current live population is not representative, either because it received a lower than average dose or for other statistical reasons.

In order to understand why ESR could give lower dose assessments a statistical analysis of the Kazakhstan population was conducted.

Statistical analysis of Kazakhstan population with implications for analyses of teeth by specific age group

According to[18] Kazakhstan's demographics are:

Median age (2004 est.)**:**
Total: 28.3 years
male: 26.6 years
female: 30 years
Age structure of Kazakhstan population:
0–14 years: 24.4% (male 1,884,369; female 1,807,585)

15–64 years: 68% (male 5,028,455; female 5,268,726)
65 years and over: 7.6% (male 404,940; female 749,629) (2004 est.)
Total male population of Kazakhstan is 7,317,764
Total female population of Kazakhstan is 7,825,940
Total female-to-male ratio: 1.07
Life expectancy at birth:
total population: 66.07 years
male: 60.72 years
female: 71.73 years (2004 est.)
The total and gender age distribution of the Kazakhstan population can be modeled based on the above data and polynomial fit. Our results of such modeling are presented in Figs. 1–3. Table 3 shows the stages of development of permanent human teeth in the countries of the former USSR.[19] In order to determine the age when the onset of the dose accumulation in tooth enamel takes place, at least two fac-

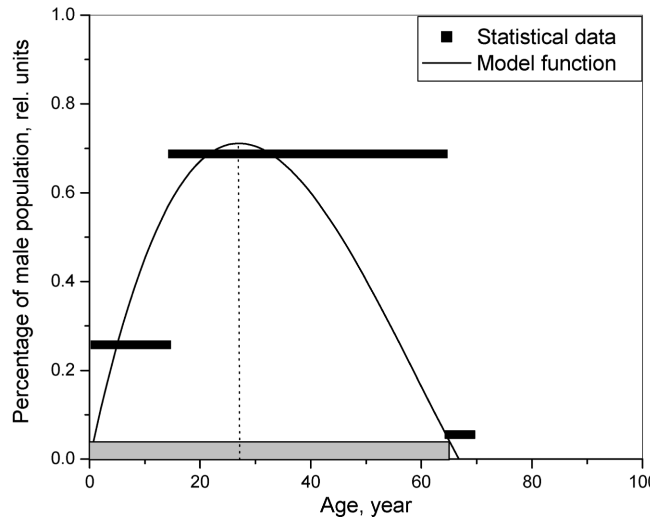

Fig. 2. Kazakhstan male population age distribution.

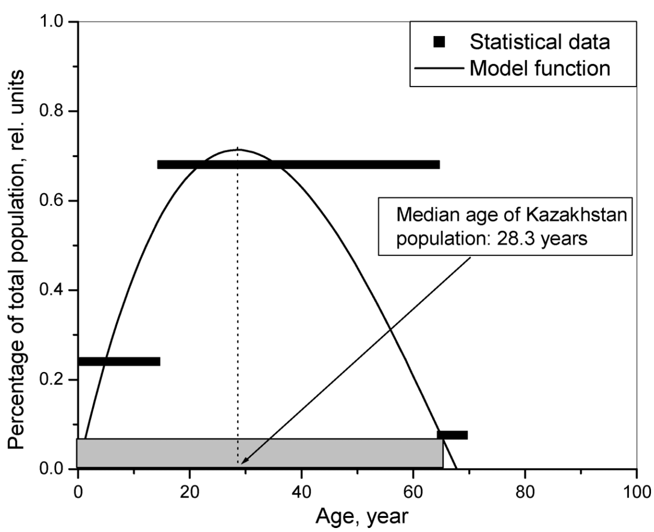

Fig. 1. Total Kazakhstan population age distribution.

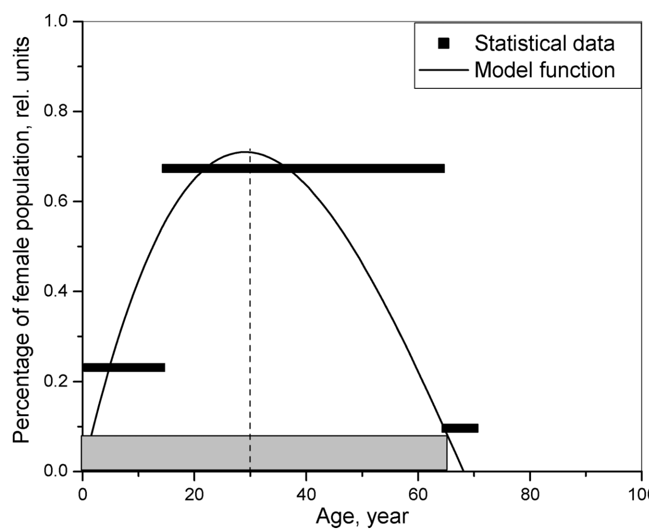

Fig. 3. Kazakhstan female population age distribution.

Table. 3. Typical ages of tooth formation based on data extracted from.[19]

Tooth pos.	Follicle creation	Start of mineralization	Completion of enamel formation	Eruption	Root formation
1	8 mo. of gestation	6 mo.	4–5 y	6–8 y	10 y
2	8 mo. of gestation	9 mo.	4–5 y	8–9 y	10 y
3	8 mo. of gestation	6 mo.	6–7 y	10–11 y	13 y
4	2 y	2.5 y	5–6 y	9–10 y	12 y
5	3 y	3.3 y	6–7 y	11–12 y	12 y
6	5 mo. of gestation	9 mo. of gestation	2–3 y	6 y	10 y
7	3 y	3.5 y	7–8 y	10–12 y	15 y
8	5 y	8 y	varies	varies	no limit

Table 4. United Nations data for the Kazakhstan population in 1998.[23]

Age group	Total population		Male population		Female population	
	$\times 10^3$	% of total	$\times 10^3$	% of total	$\times 10^3$	% of total
All ages	15034	100	7239	48.15	7794	51.85
> 50	2763	18.38	1132	7.53	1630	10.84
> 55	2203	14.65	872	5.80	1330	8.85
> 60	1724	11.47	663	4.41	1060	7.05
> 65	1044	6.94	366	2.43	678	4.51
> 70	708	4.71	223	1.48	485	3.23

tors need to be taken into account. First, only molars and premolars (tooth positions 4–8) are suitable for ESR dose reconstruction because front teeth have considerable dose contribution from solar light.[20,21] Second, mineralization of tooth enamel takes place in two stages, formation and maturation.[22] In the first stage an immediate partial mineralization of tooth enamel occurs in the matrix segments; chemical analyses show only 25% to 30% of the eventual total mineral component. The second stage, or maturation, is characterized by gradual completion of enamel mineralization. Tooth enamel maturation continues for several years after tooth eruption.[22] At this stage, the hydroxyapatite crystals that have appeared in the first stage of mineralization continue to grow in size; simultaneously the organic matrix gradually becomes thinned. Taking these two factors into account an age of 10 years can be taken as median for determination of the cohort of suitable tooth donors for ESR dose reconstruction.

The first test, which was most hazardous for Dolon, took place in 1949, so people need to be at least 66 years old in 2005 to be suitable live candidates for radiation dose reconstruction in teeth. Based on Figs. 1–3 one can conclude that, in 2005, for the total Kazakhstan population the percentage of people of this age is 4.8%, men comprising only 1.86% of the total population and women (7.8%). To validate these results, Table 4 gives UN demographic data for Kazakhstan in 1998, the year of the last official census. It shows a similar trend especially if the considerable reduction in life expectancy after the break up of the Soviet Union is taken into account.

Table 1 provides available information on the number of residents in the most exposed villages. Typically populations were below 2,000; Dolon had about 1,000 residents.

Fig. 4 represents results of our calculations of the number of teeth suitable for ESR dose reconstruction from exposed village populations in Kazakhstan based on the available statistical data.[18] Thus, four times as many teeth will be collected from women than from men. Further, statistically, present day male tooth donors will not represent their local populations at the period of exposure because of the very small number of them. Also, at 66 years of age they are 10 years older than the current statistical life expectancy for Kazakh males (60.72). This may mean that radiation doses measured in teeth collected from women and men of this age and older need to be analyzed separately and compared with model dose assessments carried out specifically for the female or the male population but not for the total.

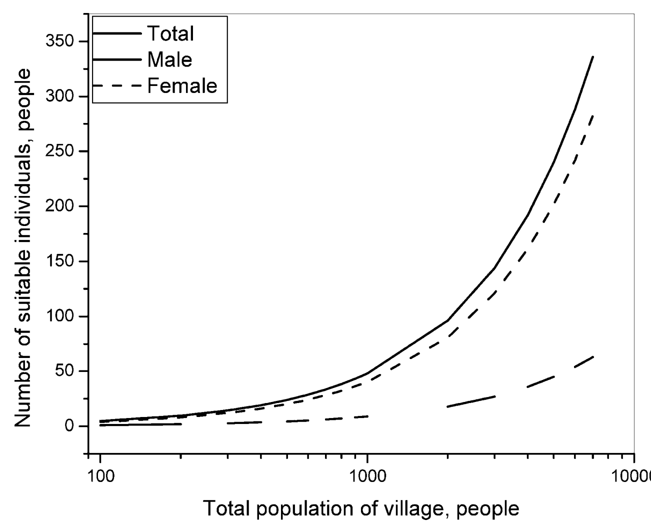

Fig. 4. Number of potential tooth donors who were living in a village and had permanent teeth in 1949 versus total population of the village. The total Kazakhstan population is shown by a solid line, the male population by a dotted line and the female population by a dashed line.

Another factor is that people who were aged between 10 and 20 at the time of exposure (and are the most probable present day tooth donors for ESR dose reconstruction and FISH (Fluorescence In Situ Hybridization)) had a different lifestyle from other age groups. For example, the schools they attended may have been outside their villages, the universities and colleges in distant larger centers. They visited grandparents in the summer time, carried out military duties and other atypical activities.

For these reasons the low number of appropriate candidates (1-20 residents) for dose reconstruction may play a critical role in a non-representative dose assessment for a given village under study.

CONCLUSION

Our statistical analysis of the Kazakhstan population has indicated the following potential problems with selection of tooth donors for dose assessment in small villages (1,000-2,000 residents) potentially overexposed as a result of early surface nuclear tests at SNTS:

- The very small number of suitable tooth donors for dose assessment (people > 66 yr) increases the chances that they will not be typical of most exposed villagers
- The extremely small number of village males older than 66 not only increases the non-representativeness of this sample but also places it outside the statistical life-expectancy of males in Kazakhstan < 60.72 yr
- Good candidates for dose reconstruction based on teeth had atypical lifestyles. These people were aged between 10 and 20 at the time of the most hazardous nuclear tests.

One possible solution to these difficulties with ESR tooth dosimetry for the Kazakhstan population is to develop special models that better reflect life patterns of the present potential tooth donors but not the population of Kazakhstan in 1949 when most hazardous nuclear tests took place. An alternative is to use archived teeth collected in the 1950s as in[9] in which high radiation doses were found.

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